

Closing the Low-mass Axigluon Window

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Abstract. In this report, I will present the current status of the low-mass axigluon. The axigluon is a massive, color octet, axial vector boson, predicted in, *e.g.*, chiral color models and some technicolor models, with a mass of order the electroweak scale. Axigluons with a mass larger than about 125 GeV to nearly 1 TeV can be eliminated by di-jet production at hadron colliders like the TEVATRON, but a low-mass window exists that the di-jet search can not probe. Υ decays can rule out axigluons with a mass up to 25 GeV , and low energy e^+e^- (PEP and PETRA) can rule out axigluons with a mass up to 50 GeV using a measurement of R . Top production at the TEVATRON disfavors a light axigluon. A measurement of R at LEP **strongly** disfavors a light axigluon, and rules out an axigluon with mass $< 365\text{ GeV}$.

MOTIVATION

The possible existence of an axigluon was first realized in chiral color models [1], where the gauge group of the strong interaction is extended from $SU(3)_C$ to $SU(3)_L \times SU(3)_R$. At low energy, this larger color gauge group breaks to the usual $SU(3)_C$ with its octet of massless vector gluons, but it leaves a residual $SU(3)$ with an octet of massive, axial vector bosons called *axigluons*. In these chiral color models, the axigluon is expected to have a mass of order the electroweak scale. Similar states are predicted in technicolor models [2].

In order to search for these states, Bagger, Schmidt and King [3] noted that the di-jet cross section at hadron colliders would be modified by the addition of s -channel axigluon exchange. Searches were performed by the UA1 and CDF collaborations, with limits of $150\text{ GeV} < M_A < 310\text{ GeV}$ by UA1 [4] and $120\text{ GeV} < M_A < 980\text{ GeV}$ by CDF [5]. Given additional center of mass energy and/or luminosity, these di-jet searches at hadron colliders will easily raise the upper exclusion limit, but it will be difficult to decrease the lower exclusion limit.

Several additional search strategies were suggested involving the Z^0 and the large amounts of data taken by the LEP experiments. Rizzo [6] suggested $Z^0 \rightarrow q\bar{q}A$ and Carlson, *et al.*, [7] suggested $Z^0 \rightarrow gA$ going through a quark loop. These suggestions involve low rates, and the former requires precision multi-jet reconstruction.

In the remainder of this report, I will address some additional search strategies for the axigluon, and report on the current status of the search.

Υ DECAYS TO REAL AXIGLUONS

The decay of the Υ family is an ideal area to search for low mass, strongly interacting particles. In the Standard Model, the dominant hadronic decay mode of any heavy vector quarkonium state ($J^{PC} = 1^{--}$) is the 3 gluon mode, $V_Q \rightarrow ggg$, where Q refers to the specific flavor of heavy quark. The decay to a single gluon is forbidden by color, while the decay to 2 gluons is forbidden by both the Landau-Pomeranchuk-Yang theorem [8] (which forbids the decay of a $J = 1$ state to 2 massless spin 1 states) and quantum numbers ($C = -1$ for the gluon, so an odd number of gluons are needed for this particular decay). The leading order decay rate of a heavy quarkonium state to 3 gluons is well known:

$$\Gamma(V_Q \rightarrow ggg) = \frac{40(\pi^2 - 9)\alpha_s^3}{81\pi M_V^2} |R(0)|^2 \quad (1)$$

where M_V is the quarkonium state's mass and $R(0)$ is the non-relativistic, radial wavefunction evaluated at the origin.

A heavy, vector quarkonium state **may** decay into a gluon plus an axigluon. As the axigluon is massive, the Landau-Pomeranchuk-Yang theorem is avoided, and the axigluon has $C = +1$. The decay rate for $V_Q \rightarrow Ag$ is given by [9]:

$$\Gamma(V_Q \rightarrow Ag) = \frac{16\alpha_s^2}{9M_V^2} |R(0)|^2 (1 - x)(1 + \frac{1}{x}) \quad (2)$$

where $x = \left(\frac{M_A}{M_V}\right)^2$. Both this decay rate and the leading order Standard Model rate depend on the non-relativistic radial wavefunction; a ratio of these two decay rates does not depend on the wavefunction, and, as such, had much less uncertainty. The ratio is given by:

$$\frac{\Gamma(V_Q \rightarrow Ag)}{\Gamma(V_Q \rightarrow ggg)} = \frac{18\pi}{5\alpha_s(\pi^2 - 9)} (1 - x)(1 + \frac{1}{x}) \quad (3)$$

Notice that, since the gluon plus axigluon mode has one fewer power of α_s , the ratio is large (the numerical factor in front of the kinematical structure is approximately 100).

This ratio, as a function of x is shown in Figure 1. The addition of this new hadronic decay mode will at least double the hadronic width of a vector quarkonium state, even for an axigluon mass nearly equal to the quarkonium state mass. Using this process and the Υ system, we can exclude an axigluon with mass below about 10 *GeV*. A analysis by Cuyper and Frampton [10] yielded quantitatively similar conclusions.

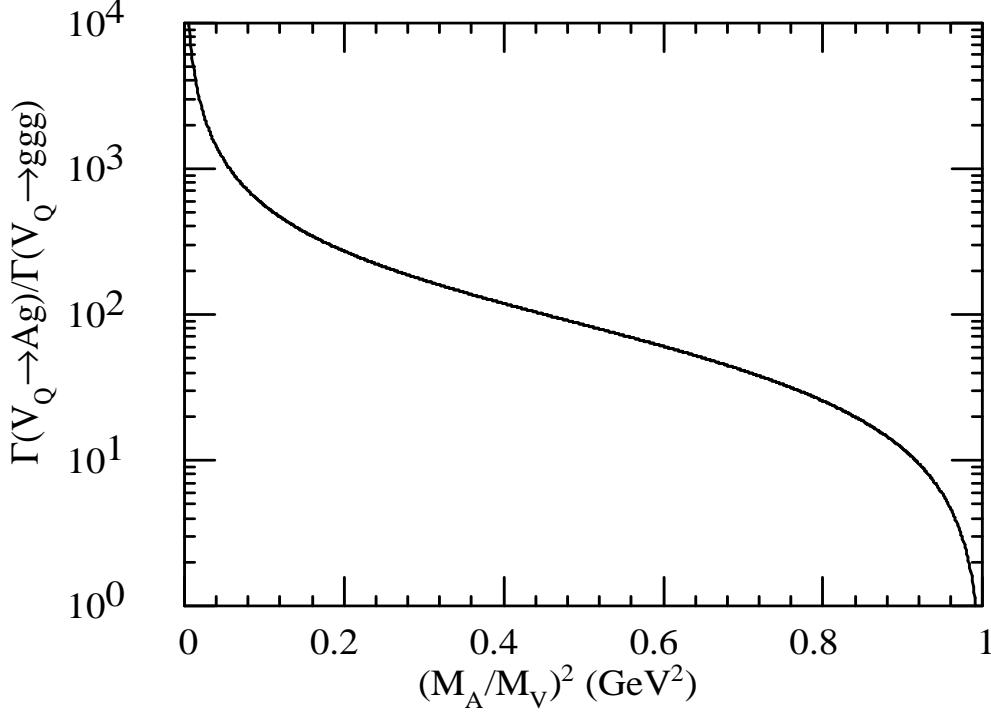


FIGURE 1. Ratio $\frac{\Gamma(V_Q \rightarrow Ag)}{\Gamma(V_Q \rightarrow ggg)}$ for the decay of a heavy quarkonium state to a real axigluon.

Υ DECAYS TO VIRTUAL AXIGLUONS

In addition to Υ decays to real axigluons, it is possible to study Υ decays to virtual axigluons, $\Upsilon \rightarrow gA^*(\rightarrow q\bar{q})$. The decay rate is given by [11]

$$\Gamma(V_Q \rightarrow q\bar{q}g) = \frac{2^8 n \alpha_s^3}{3^5 \pi} \frac{M_V^2}{M_A^4} F(x) |R(0)|^2 \quad (4)$$

where n is the number of active quark flavors (in this case 4) and

$$F(x) = \frac{3}{2} x^2 \left(2x \ln \left(\frac{x}{x-1} \right) - 2 - \frac{1}{x} \right). \quad (5)$$

As before, we can look at the ratio of this hadronic width to the dominant Standard Model width:

$$\frac{\Gamma(V_Q \rightarrow q\bar{q}g)}{\Gamma(V_Q \rightarrow ggg)} = \frac{128 F(x)}{15(\pi^2 - 9)x^2}. \quad (6)$$

This time, there is no large numerical factor. This ratio is shown in Figure 2. The dashed lines in the figure indicate 2 possible exclusion limits that can be made

using data. The more conservative estimate is to argue that our knowledge of the Υ width is such that a correction to the standard width larger than 50% is unacceptable; thus, this ratio is smaller than 0.5, which gives an upper exclusion limit of $M_A < 21 \text{ GeV}$. A less conservative estimate is to compare this correction to the expected rate to QCD radiative corrections to the Standard Model rate and other possible contributions to the hadronic width (*e.g.*, $\Upsilon \rightarrow \gamma^* \rightarrow q\bar{q}$), and argue that another correction larger than these is unacceptable. In this case, the ratio must be less than 0.25, excluding axigluons with mass smaller than 25 GeV .

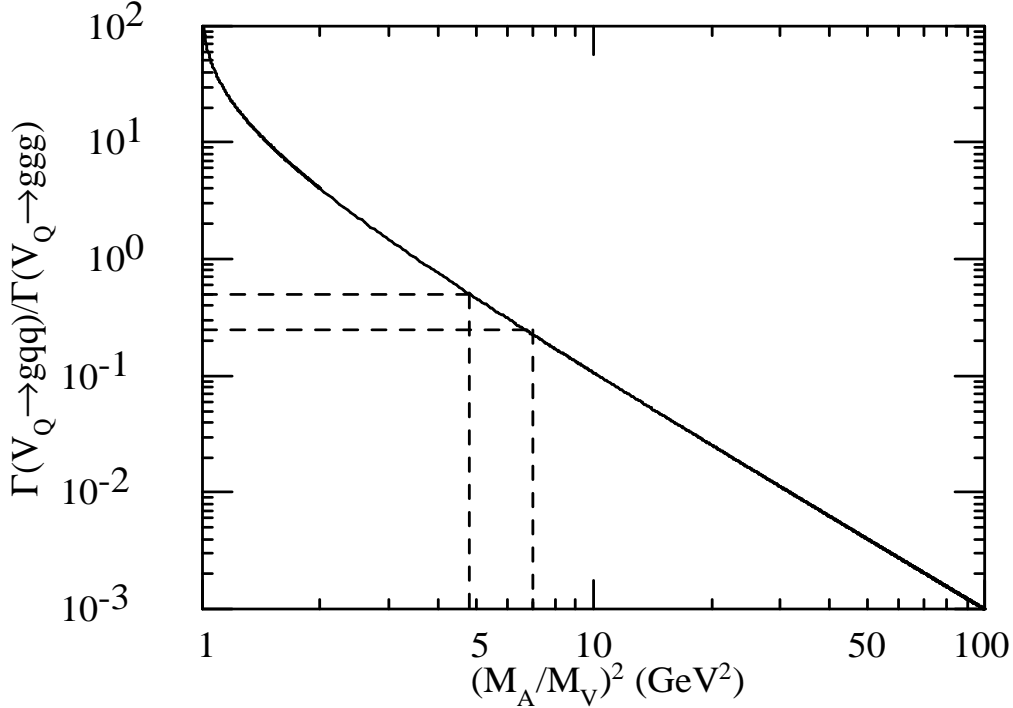


FIGURE 2. Ratio $\frac{\Gamma(V_Q \rightarrow q\bar{q}A)}{\Gamma(V_Q \rightarrow ggg)}$ for the decay of a heavy quarkonium state to a virtual axigluon. The dashed lines indicate 2 possible exclusion limits.

Not long after our work on the Υ , Cuypers and Frampton and Cuypers, Falk and Frampton [12] published papers on the R value in e^+e^- collisions at low energy. They included the full set of QCD radiative corrections, including axigluon radiative corrections, to the tree level process. They exclude an axigluon with $M_A < 50 \text{ GeV}$ using PEP and PETRA data.

TOP PRODUCTION

The top is too short lived to allow for a toponium state; if it did, the same techniques that worked in the Υ system would work for toponium as well. On the other hand, because of the large mass of the top, top production is inherently perturbative, $q\bar{q} \rightarrow t\bar{t}$ is well understood, and it can be used to search for a light axigluon. The parton level cross section for $q\bar{q} \rightarrow t\bar{t}$, due to an s -channel gluon, is well known:

$$\left(\frac{d\sigma}{d\hat{t}}\right)_0 = \frac{1}{16\pi\hat{s}^2} \frac{64\pi^2}{9} \alpha_s^2 \left[\frac{(m^2 - \hat{t})^2 + (m^2 - \hat{u})^2 + 2m^2\hat{s}}{\hat{s}^2} \right] \quad (7)$$

and the cross section with the addition of an s -channel axigluon is [13]

$$\left(\frac{d\sigma}{d\hat{t}}\right)_{q\bar{q}} = \left(\frac{d\sigma}{d\hat{t}}\right)_0 \left[1 + |r(\hat{s})|^2 + 4\Re(r(\hat{s})) \frac{(\hat{t} - \hat{u})\hat{s}\beta}{(\hat{t} - \hat{u})^2 + \hat{s}^2\beta^2} \right] \quad (8)$$

where $r(\hat{s}) = \frac{\hat{s}}{\hat{s} - M_A^2 + iM_A\Gamma_A}$ and β is the top quark velocity parameter, $\beta = \sqrt{1 - \frac{4m^2}{\hat{s}}}$. The addition of an s -channel axigluon affects both the total cross section and the forward-backward asymmetry (only the interference term affects the forward-backward asymmetry).

The results on total cross section are shown in Figure 3. From the relatively good agreement between experimental values of the top cross section [14,15] and theoretical calculations [16,17], we can say that an axigluon is disfavored by top production cross section, but nothing conclusive can be said.

Shown in Figure 4 is the forward-backward asymmetry in top production as a function of axigluon mass. Without an axigluon, the asymmetry is identically zero.

MISCELLANEOUS

Unitarity is violated, in that $Q\bar{Q} \rightarrow Q\bar{Q}$ will be non-perturbative unless

$$M_A > \sqrt{\frac{5\alpha_s}{3}} M_Q \quad (9)$$

as pointed out by Robinett [18]. Using the top quark as Q , this leads to a lower limit on the axigluon mass of $M_A > 73 \text{ GeV}$ [19].

Higgs searches, *e.g.*, by CDF, can make use of the process $p\bar{p} \rightarrow W + X^0$, where X^0 is the neutral Higgs boson, and it is assumed to decay to $b\bar{b}$ [20]. The limit on Higgs boson mass is such that $\sigma \cdot BR > 15 - 20 \text{ pb}$ are not allowed. The same final state is possible with an axigluon in place of the Higgs boson; we find the part level cross section for $q\bar{q}' \rightarrow WA$ to be [19]:

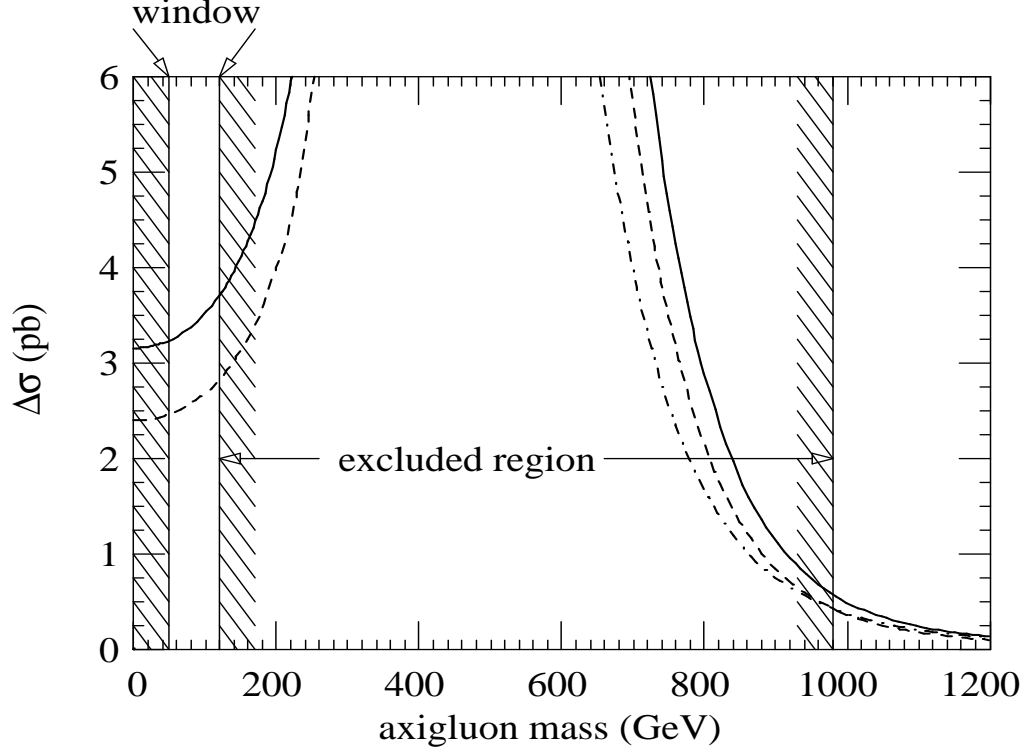


FIGURE 3. Difference in top production cross section, based on the presence of an axigluon. The different curves are for different sets of leading order parton distribution functions, and different choices for axigluon width. The solid (dotdashed) line is for the “new” Duke and Owens pdf’s with $\Gamma_A = 0.1M_A$ ($0.2M_A$); the dashed line is for CTEQ4L with $\Gamma_A = 0.1M_A$.

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{4\alpha_s}{9} \left[\frac{G_F M_W^2}{\sqrt{2}} \right] \frac{|V_{qq'}|^2}{\hat{u}\hat{t}\hat{s}^2} \left[\hat{u}^2 + \hat{t}^2 + 2\hat{s}(M_W^2 + M_A^2) - \frac{M_A^2 M_W^2 (\hat{u}^2 + \hat{t}^2)}{\hat{u}\hat{t}} \right]. \quad (10)$$

Assuming $BR(A \rightarrow b\bar{b}) = \frac{1}{5}$, and calculating the cross section for the associated production of $W + A$, a conservative lower limit of $M_A > 70 \text{ GeV}$ is possible, using the same analysis at the Higgs search.

Finally, we can examine the value of α_s , extracted from low energy data but run up to M_Z to the value of α_s extracted from the hadronic width of the Z^0 at the pole. Since the axigluon mass is expected to be at least 70 GeV , the running of α_s should not be affected much by the axigluon. Then, the R value at low energy, or the hadronic width at the Z^0 pole, is subject to a correction from real and virtual axigluons [12], of the form:

$$\left[1 + \frac{\alpha_s(\sqrt{s})}{\pi} f\left(\frac{\sqrt{s}}{M_A}\right) + \mathcal{O}(\alpha_s^2) \right] \quad (11)$$

where the function $F(\sqrt{s}/M_A)$ is calculated in Ref. [12]. The Particle Data

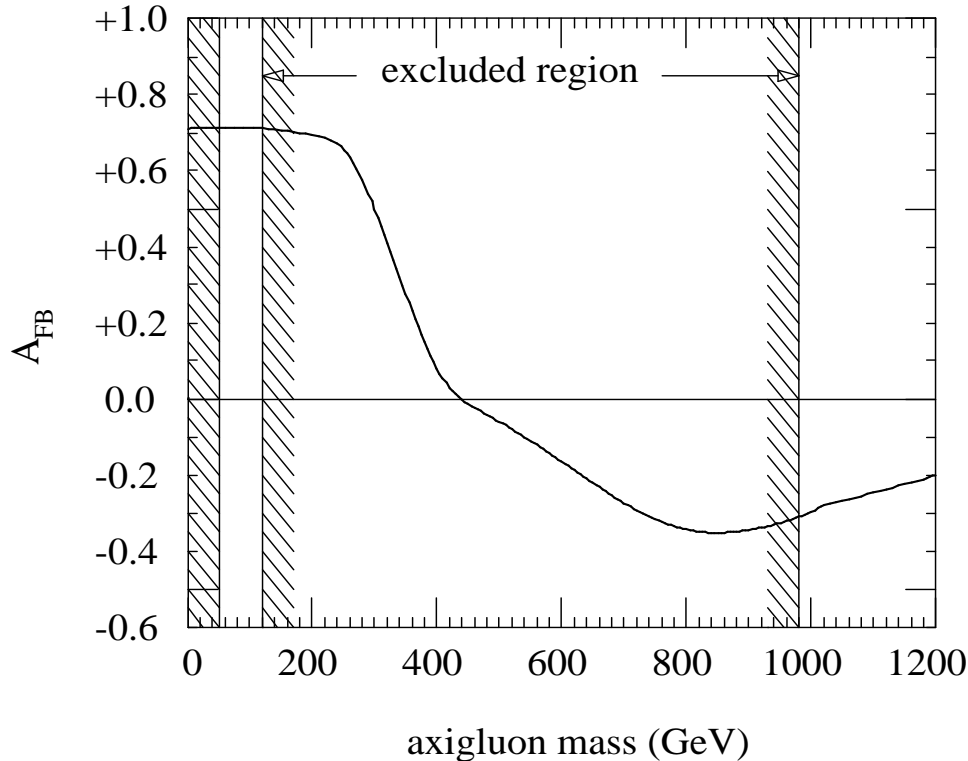


FIGURE 4. Top production forward-backward asymmetry.

Group [21] quotes a value of α_s from various low energy data run up to M_Z as $\alpha_s^{(LE)} = 0.118 \pm 0.004$, while the extraction from the hadronic width of the Z^0 at M_Z as $\alpha_s^{(HE)} = 0.123 \pm 0.004 \pm 0.002$. Attributing the difference in the extracted values of α_s to the axigluon gives bounds on the $f(\sqrt{s}/M_A)$ term, such that $f(M_Z/M_A) \leq 0.042 \pm 0.050$. This implies that $f(M_Z/M_A) < 0.092(0.142)$ at the 65% (95%) level, and that $M_Z > 570 \text{ GeV}(365 \text{ GeV})$ at the same confidence levels. Should the agreement between the low energy and high energy extractions of α_s increase, the corresponding lower limit on the axigluon mass would also increase.

CONCLUSIONS

The existence of an axigluon is predicted in chiral color models. A low-mass axigluon is difficult to exclude in typical collider experiments (*e.g.*, using di-jet data). Other approaches must be used to rule out axigluons with masses below 125 GeV . Υ decay, top production, unitarity bounds and associated production of a W boson with an axigluon can exclude axigluons with mass below about 70 GeV . A comparison of α_s as extracted in low energy experiments and high energy experiments can rule out an axigluon with a mass lower than 365 GeV .

This completely closes the low-mass axigluon window, and when combined with the CDF limits, an axigluon with mass below about 1 TeV is not allowed. An axigluon, if it exists, is in the realm of TeV physics.

ACKNOWLEDGEMENTS

I would like to acknowledge the support of Penn State through a Research Development Grant and the Mont Alto Faculty Affairs Committee's Professional Development Fund. I would like to thank Rick Robinett for carefully reading this manuscript.

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